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Variable Automata as Discrete Descriptions of Homeostasis, Morphogenesis, Cognition and Autopoiesis in Organismic Networks

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Abstract

The question of a *variable* `automaton', or an automaton with a *varying* internal structure goes back to Norbert Wiener's suggestion in his book on ``*The Human Use of Human Beings*'' (*Cybernetics and Society*, 1954). However, in his popular book, Wiener did not attempt any formal, or mathematical, definition of a `variable automaton'. Because the state space S of a standard, rigid automaton (or sequential machine/Turing machine) is known to have a semigroup (or monoid) structure, one may consider as the basis for a continuously varying automaton the mathematical concepts of topological semigroup or topological groupoid (such as, for example, a Lie groupoid). In the more general context of Category Theory, the automaton may be defined by a monoidal category (or monoid category), and then a `variable automaton' can be defined as an automaton supercategory, thereby replacing the rigid state space of an automaton with a supercategory of monoidal (automaton) category of automata state spaces and automata homomorphisms (more specifically homeomorphisms in the case of topological semigroups or Lie groupoids). Such monoid supercategories may provide either a simplified, discrete or a dynamic representation of living organisms as Norbert Wiener's intention was in his book about Cybernetics and Society. Precise mathematical definitions of variable automata are presented, and their possible applications to improved powerful automation, fuzzy systems, modeling functional cells, living organisms, ecosystems, and (maybe) also human societies are briefly considered.

1.1 Introduction

The question of a *variable 'automaton'*, or an automaton with *varying* internal structure goes back to Norbert Wiener's suggestion in his book in reference [1] 1. He was one the founders of Cybernetics and a convinced advocate of automation, as well as having a strong interest in exploring how automation and cybernetics may influence society. In doing so he also speculated that more powerful machines than automata could be built that have a *varying structure* which can be called *'variable automata'* (VAs). He also suggested that such VAs may mimic quite well the behavior(s) of living organisms, perhaps including *human* ones– insofar as human biology and physiology is concerned. His view of Cybernetics was that of a science of control mechanisms, or governing and automation, conceived not only with technological applications, but also with relevance to cognitive, biological organisms, and human societies [1]. Thus, Norbert Wiener defined *Cybernetics* in the 1950s as *"the scientific study of* **control and communication** *in the animal and the machine."*[2]. The name of Cybernetics itself is derived from the Greek word *cyberos*, with the meaning of "steering" or "navigating". It has also acquired the meaning of an *organizational theory*.

A related ontological theory of *"Autopoiesis"* was developed in philosophical terms in 1973 by the biologists Humberto Maturana and Francisco Varela (*v. infra*). The word "autopoiesis" is also derived from the Greek words "auto"-meaning 'self', and "poiesis"-meaning 'production' or 'creation'. In other words, the term was designed to represent organisms as *'machines that are organized as unified networks of processes of components' production that continuously regenerate and realize the network of processes and relations that produced them'*. Because organisms are considered by the original autopoiesis theory as a special type of 'machines' this view of functioning organisms is elated to (Bio)-Cybernetics. However, an *'autopoietic system'* was said to be defined in contrast with an *'allopoietic'* system, such as a car factory that uses raw materials (components) to generate a car (that is, a system with an organized structure)– which is something else than the factory itself that produced the car. Moreover, an autopoietic system is *autonomous and operationally closed*, in the sense that there are sufficient processes within it to maintain the whole 'system'. On the one hand, the use of the term 'machines' in the above definition if taken in a strict sense could be somewhat misleading because it might be considered as restricting the theory to a description of functional organisms in terms of classical automata as further discussed in the sequel. However, the contrast in the autopoietic theory of autopoietic systems with "allopoietic" ones that do admit a classical automaton description but do not self-repair or 'self-reproduce' themselves suggests perhaps that the term 'machine' in the definition of autopoiesis should not be taken to specify sequential machine or automaton in the precisely defined mathematical sense. It may have been simply employed to suggest some kind of classical, deterministic 'system', or maybe an abstract, vague 'description' of *"unified networks of processes of components"*,

that is some sort of general system for which one can define mechanisms that would possibly lead to the repair and self-copying/production of itself. If the latter were indeed the intended meaning of the words 'autopoietic system' then one could always define a Metabolic-Repair-Genetic system, or $[(M,R),G]$-system obtained by extending the simple Metabolic-Repair (M,R)-systems introduced by Robert Rosen in terms of categories of sets [12-13]; the extension of the (M,R) system would consist in genetic components or specific β- mappings of sets that can repair or replace the repair components R in order to maintain and/or duplicate the simple (M,R)-system [13]. Whereas such a definition of an 'autopoietic system' would be precise, the issue of such an 'autopoietic system' being in fact a special kind of classical automaton comes up again because all (M,R)-systems have classical automata or sequential machines as their canonical representation; in this case, it turns out that such 'autopoietic systems' defined by $[(M,R),G]$s are indeed a special kind of machines–with the usual meaning of the word as classical automata– that could self-repair and self-reproduce both their metabolic and repair components. Then, one is still left with the question of how G-components are being reproduced and/or repaired, which has been already answered in part by subsequent developments of Rosen's relational theory of simple (M,R)-systems and their dynamic realizations in [14].

Furthermore, autopoietic systems are said to be "*structurally coupled*" with their medium, in the sense of being embedded in the dynamics of changes that resemble 'sensory-motor' coupling. Such continuous dynamics are considered in the original autopoiesis theory as a 'rudimentary' form of knowledge, or a primitive form of *cognition*, that could be therefore observed in the cell(s) of all living organisms. Thus, according to the original autopoiesis theory, cognition is *included* in autopoiesis. On the one hand, Maturana stated however that he would *"never use the notion of* **self-organization**, *because it cannot be the case... it is impossible"*. On the other hand, the formation of a molecular crystal such as those formed by oriented A-DNA fibers, or a biomembrane, involves the 'self'-assembly of molecules into an organized lattice in the A-DNA fiber case, or the self-association/aggregation of both lipids and membrane proteins into a 'liquid crystal' bilayer in the case of a biomembrane; both these cases have the hallmark of a simple form of 'self'-organization, however without the need for assuming any 'self-referential' mechanism or teleological process.

Subsequently, Jerome McGann– citing Maturana and Varela– defined *an autopoietic system* as "**a closed topological space that 'continuously generates and specifies its own organization through its operation as a system of production of its own components, and does this in an endless turnover of components'**. Homeostasis–which is widely accepted by physiologists– is no less than such coordinated and organized processes that were re-claimed by the original autopoiesis theory. Therefore, this part of the autopoietic theory is neither disputed nor is it novel. Jerome McGann also, concluded that "autopoietic systems are thus distinguished from allopoietic systems, which are Cartesian and which 'have as the product of their functioning something different from themselves' ". Upon this view, autopoietic systems are 'self-referential' and also 'self-reproduce'. Critics have subsequently argued that the term autopoiesis and the autopoietic theory fail to define or explain living systems and that, because of the extreme language of *self-referentiality* that it uses without any external reference, it is really an attempt to give substantiation

to Maturana's radical constructivist or solipsistic epistemology. Rod Swenson argued that autopoietc theory is *"miraculously decoupled from the physical world by its progenitors [...] (and thus) grounded on a solipsistic foundation that flies in the face of both common sense and scientific knowledge"*.

Be that as it may form an ontological/philosophical point of view, there are also fundamental, *logical* issues and problems even with the current variations and flavors of autopoietic theories. One such attempt made in ref. [3] is to separate conceptually a re-defined 'PB-JS autopoiesis' from 'cognition', and then define a living 'system' as one which is at the intersection of autopoietic systems with cognitive ones, that is *"a system which is both autopoietic and cognitive"* [3]. However, such a separation between autopoiesis and cognition also appears in the title of the 1973 original book on these subjects [5]. Moreover, the introduction of *'random dynamical systems'* in [3] departs from the deterministic approach of the original autopoiesis theory without solving however the problem of explaining how biological organization emerged and how its functional structure is maintained in a non-random manner, albeit subject to senescence and ageing. Even the introduction of 'chaotic systems' does not solve this basic problem of biological evolution and maintenance of organizational structure in all functional organisms.

The first four logical problems, or issues, with both autopoietic and cybernetic theories– that consider living organisms as either **machines** or 'systems'– are as follows

1. The operational logic of all machines/automata and computers is two-valued, Boolean, whereas *a priori* one has no basis to assume that living organisms, or even physiologically functional cells in a multi-cellular organism have Boolean operational logic. (In fact, it has been already proposed that the operational logic of genetic networks and neural ones is multi-valued).

2. Both dynamical systems and automata have a **fixed** structure or rigid 'internal organization' dictated by their operational Boolean logic and their logical design; thus, the transition function of machines/classical automata and classical dynamical systems is fixed. To avoid this limitation Norbert Wiener proposed to consider living organisms as 'variable' automata (VAs), without however providing a formal definition of VAs; such a formal definition was however published in 1971 in ref. [4], two years before the original publication of the autopoiesis theory of Varella and Maturana [5].

3. Complete self-reproduction and operationally 'closed', self-referential systems require a special type of Quine logic axiom which is independent of both Boolean logic and 'standard' set theory [7].

4. When considering functional cells as some kind of 'machines' in the context of general theories it is often deliberately or unintentionally ignored the basic fact that the unified networks are molecular, and thus **quantum** in nature, and therefore their operational logic has an underlying *quantum logic*. This critique is equally applicable to autopoiesis theories, and Descartes', or Norbert Wiener's, view of animals as 'machines' that seem to have ignored completely the quantum-molecular aspects of living cell networks and

organisms. From the single-cell *Euglena viridis* to the higher plants, at the center of their very existence are *quantum*, photosynthetic processes. Moreover, without plants and photosynthesis the huge animal part of the entire biosphere could not survive; the only forms of life left would then be anaerobic bacteria and certain viruses hosted by such bacteria.

The fourth logical issue leads to the possibility of considering organisms as molecular 'machines', or "quantum automata"[4] in which *local, quantum* interactions play very important roles for energy storage, 'self-assembly' of biomembranes through hydrophobic interactions (London dispersion forces) that are quantum in their nature, as well as in biochemical processes such as: DNA-duplication, RNA-transcription, enzyme mechanisms, specific molecular recognition, protein biosynthesis, and so on. Similarly, the 'strong coupling with the medium/environment' postulated by autopoietic theories can only be realized and acquire meaning in the case of living cells through locally defined, quantum interactions at the cell surfaces and in the biomembrane pores or channels through which the cell communicates with its (usually aqueous) environment.

In the next section, formal definitions of both rigid/classical and variable automata are introduced, without however making the claim that such variable 'systems' would be intrinsically capable of either 'autopoiesis' or 'cognition' when the latter are defined in some precise sense. Nevertheless, VAs may provide many useful models of physiologically functional cells and living organisms, natural selection processes and evolution, because they provide flexible structures and dynamics capable of reproduction and quasi- self-reproduction, in the sense of generating structurally equivalent systems without assuming either identity of the offspring or complete self-reproduction; therefore, such VAs are **not** *self-referential*, and are not autopoietic. One may however conjecture that VAs are capable of certain forms of *cognition*, without claiming that such 'cognition' would be either equivalent or identical to those occurring in living organisms.

1.2 Automaton Definitions

A classical automaton, *s-automaton* $\mathcal{A}$, or 'sequential machine', is defined as a quintuple of three sets: I,O and S, and two set-theoretical mappings:

$$(I, O, S, \delta : I \times S \to S; \lambda : S \times S \to O),$$

,

where I is the set of s-automaton inputs, S is the set of states (or the state space of the s-automaton), O is the set of s-automaton outputs, δ is the *transition function* that maps a s-automaton state s_j onto its next state s_{j+1} in response to a specific s-automaton input $j \in I$, and λ is the *output function* that maps couples of consecutive (or sequential) s-automaton states (s_i, s_{i+1}) onto s-automaton outputs o_{i+1} $((s_i, s_{i+1}) \mapsto o_{i+1}$, hence the older name of 'sequential machine' for the s-automaton).

1.2.1 Notes:

1. The set of automaton, or sequential machine, states S –which defines the discrete *'state space'* of the automaton– has the algebraic structure of a finite semigroup (or monoid) under the operation $*$ of concatenation of sequential states.

2. With the above formal definition of automaton, the *category of abstract automata* can be defined by specifying automaton homomorphisms in terms of the morphisms between five-tuples representing such abstract automata, as discussed further in the next section. (For a basic textbook on Category Theory the interested readers are referred to [8].)

3. *Alternative definitions* of an automaton are also in use that employ a non-empty set of symbols α such that one can define a *configuration* of the automaton as a couple v(s, α) of a state $s \in S$ and a symbol $\alpha \in \Sigma$. Then δ defines a "next-state relation, or a transition relation" which associates to each configuration (s, α) a subset $\delta(s, \alpha)$ of S- the state space of the automaton.

4. The abstract descriptions of organisms as set categories of Metabolic-Replication systems, or (M, R)-systems [12-13], admit also a canonical representation in terms of categories of standard (classical) automata as shown in [15]. Other previous applications to linear neural networks are also widely known [10-11]. Somewhat less well-known are the more realistic *nonlinear* neuronal network models that also included stochastic behavior, first introduced by Herbert Landahl in 1945.

Example 1.1. A special case of automaton is that of a *stable automaton* when all its state transitions are *reversible*; then its state space can be seen to possess a groupoid (algebraic) structure. The *category of reversible automata* is then a 2-category, and also a subcategory of the 2-category of groupoids, or the groupoid category.

Definition 1.1. *A categorical automaton* can also be defined by a commutative square diagram containing all of the above components.

With the above automaton definition(s) one can now also define morphisms between automata and their composition.

Definition 1.2. A *homomorphism of automata* or *automaton homomorphism* is a morphism of automata quintuples that preserves commutativity of the set-theoretical mapping compositions of both the transition function δ and the output function λ.

With the previous two definitions one has now sufficient data to be able to define the category of automata and automata homomorphisms, C_A.

1.3 Categories of Automata, Cartesian Categories and Variable Automata Definitions

Definition 1.3. A *category of automata* C_A is defined as a category of quintuples $(I, O, X, \delta : I \times X \to X; \lambda : X \times S \to O)$ and automata homomorphisms $h : \mathcal{A}_i \to \mathcal{A}_j$, such that these homomorphisms commute with both the transition and the output functions of any automata $\mathcal{A}_i$ and $\mathcal{A}_j$.

A formal definition of an '**automaton with a *varying* internal structure**' is here proposed, and then extended by means of categorical concepts in the context of supercategories $\mathbb{S}_2$ of automata state spaces S_X and automata state space homomorphisms $h_{XY} : S_X \to S_Y$.

As a relatively simple example consider the case of the category of sequential, or Turing machines, T_a, which is a subcategory of the category of automata C_A.

Definition 1.4. A 'variable Turing machine' is a supercategory $\mathbb{S}^T$ of Turing machine topological semigroup (or monoid) categories S_{TX} and topological semigroup (monoid) functors $F_{T_{XY}} : S_{TX} \to S_{TY}$ between pairs of such semigroup (or monoid) categories.

Definition 1.5. In the general case of *universal Turing machines* (UTM) one simply replaces 'Turing machine' with UTM in the previous definition to obtain a formal representation of **variable** *universal Turing machines*, V_{UTM}.

1.3.1 Remarks:

1. *Automaton homomorphisms* can be considered also as transformations of automata, or as semigroup homomorphisms, when the state space, X, of the automaton is defined as a *semigroup* S_X.
2. Abstract automata have numerous realizations in the real world as : machines, robots, devices, computers, supercomputers, always considered as *discrete* state space sequential machines.
3. Fuzzy or analog devices are not included as standard automata.
4. Similarly, *variable (transition function)* automata are not included, but Universal Turing machines are.
5. Other definitions of automata, sequential machines, semigroup automata or cellular automata lead to subcategories of the category of automata defined above.
6. On the other hand, the category of *quantum automata* is not a subcategory of the automata category defined here.

7. Such variable automata or V_{UTM}s may be practically constructed for both industrial, agricultural and Biotechnology/medical applications, and perhaps also as *'nanobots'*, by employing as part of their logical operation design MV-logics, such as the LM_N-*algebraic logic*, with N being finite.

8. As suggested by Norbert Wiener in [1], and subsequently formally defined in ref.[4], variable automata considered as discrete models of variable dynamical 'systems', complex dynamic systems (CDS) and also of organisms may be useful –aside from their future technological applications– to develop sophisticated theories of biological 'systems', such as, for example, *a formal theory of natural selection and evolution of living organisms, from bacteria to humans* in terms of V_{UTM}s and organismic supercategories (OS).

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1.4 Conclusions

Precise mathematical definitions of variable automata were presented, and their possible applications to improved powerful automation, fuzzy systems, modeling functional cells, living organisms, ecosystems, and (maybe) also human societies were briefly considered.

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See also: http://pp-dev.org:8080/encyclopedia/Research-UniversalTuringMachinesOnVariableAuto

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Universal Turing Machines On Variable Automata
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